10.1 Introduction

The EN200 course concentrates on the surface hydrostatically supported ship. In particular, it examines their hydrostatics, hydrodynamics, construction and seakeeping properties. An equally important ship for any military fleet is the submarine. As a combatant, the submarine played significant roles in both the major wars of this century. With the advent of the ballistic missile submarine, it played an equally important role in the ‘cold war’.

The use of submarines in commercial fleets is severely limited. This is mainly due to their significant operating costs. However, with the increasing use of the seas, in particular the retrieval of mineral wealth, the submarine or submersible will have an increasing role. Additionally, with the cost of space exploration becoming prohibitive, more and more attention is being paid towards the colonization of the seas. In the future, the family submersible could be the realistic alternative to the family sedan.

This chapter will explore the hydrostatic and hydrodynamic properties of submarines and compare them with those possessed by surface ships. In many instances the differences will be considerable. It will also look at the structure, construction and layout of submarines and their dynamic behavior.

10.2 Submarine Construction and Layout

You will recall from Chapter 6 that ships are constructed with a structure dependant upon the primary load they have to withstand.

- **Longitudinal Bending** Wave action causes the ship to Hog or Sag creating successive compressive and tensile stresses in the structure, particularly the keel and weather deck. Longitudinals are used to combat these stresses.

- **Hydrostatic Pressure** Water pressure attempts to crush the ship from the sides. Transverse frames combat this loading.

Most modern ships use a combination of longitudinals and transverse frames as they are subjected to both load systems.

By far the biggest load the submarine has to withstand is hydrostatic pressure. Consequently, it should be no surprise to learn that they are transversely framed. Figure 10.1 illustrates typical typical submarine construction.

10.2.1 Inner Hull

There are in fact 2 hulls in a submarine. The inner hull or pressure hull (or "people tank") holds all the pressure sensitive systems of the submarine, this includes submariners. So the inner hull has to withstand the diving depth hydrostatic pressure. You will recall that absolute pressure is given by the following:

$$P_{abs} = P_{atm} + \rho g h$$

$$\textit{where} \quad \rho g h = \textit{hydrostatic pressure} = P_{gauge}$$

A useful thumb rule is that pressure increases by 44 psi per 100ft of depth.

Any ingress of water into the inner hull can have a considerable effect upon submariner morale. Consequently, the inner hull has to be strong. As inferred above, it is transversely framed and has thick plating. The number of transverse frames and thickness of plating used is a compromise between cost, weight, operating ability and space. For examples. more frames and thicker plating means higher cost, greater weight, less space for equipment and crew but a greater operating ability because of a greater diving depth.

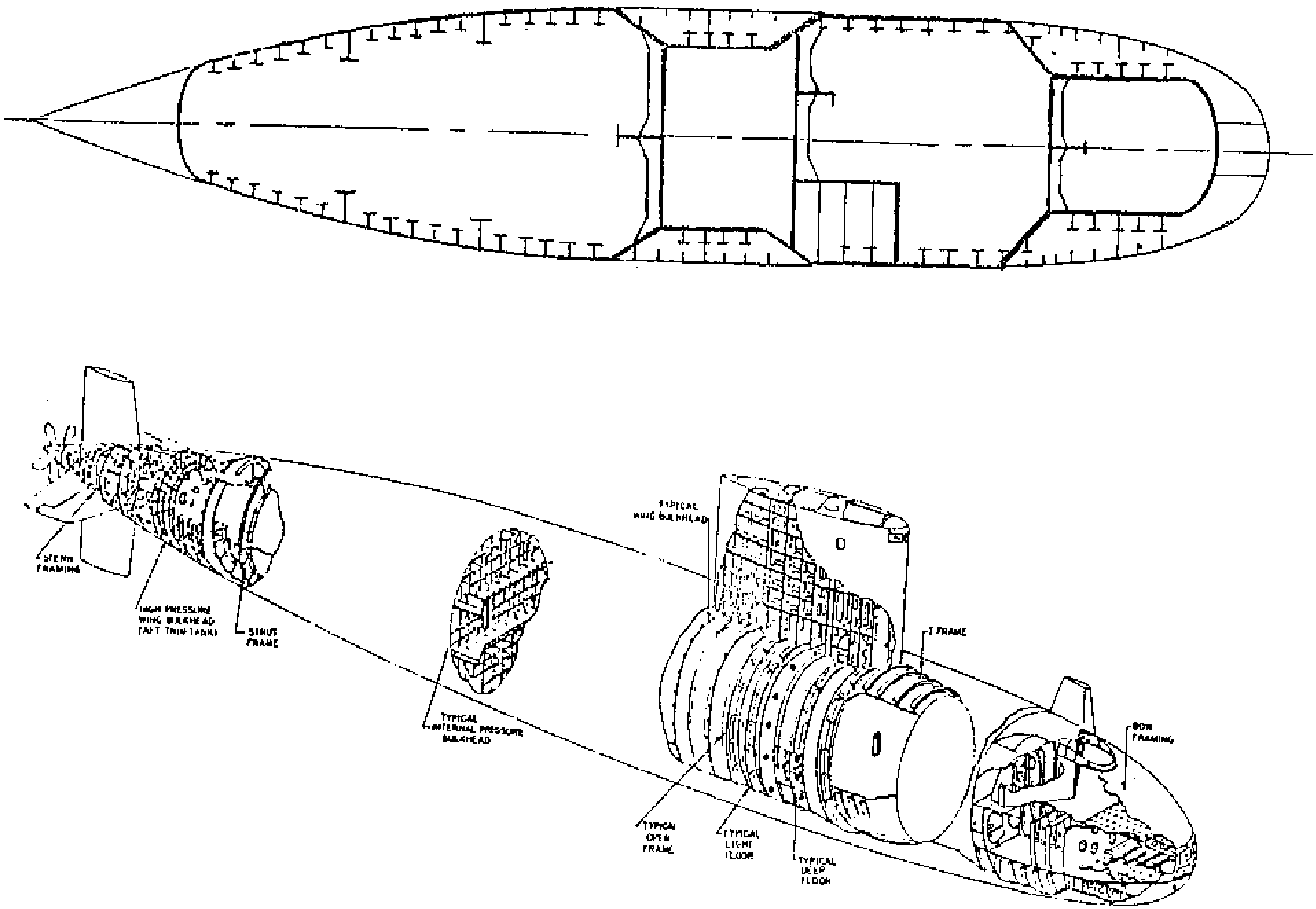

Figure 10.1 - Typical Submarine Construction

Inner hull sections are perfectly circular. Any “out of roundness” has a significant impact on its ability to support the hydrostatic load. For example, a 0.5% deviation from a perfect circle reduces the hydrostatic load carrying capacity of a submarine structure by over 35%.

It is also important that the inner hull remains within its elastic limit, even at high levels of stress. You will recall from Chapter 5 that this will occur provided the hull material remains below the yield stress $ó_y$. Consequently, very high strength steels are used with high yield stresses. Some of the more advanced Russian Submarines use Titanium for their inner hulls.

10.2.2 Outer Hull

Figure 10.1 shows that in certain places down the length of a submarine, the inner hull reduces in cross section and is surrounded by an outer hull or submarine fairing. The outer hull is simply a smooth fairing that covers the non-pressure sensitive equipment of the submarine such as Main Ballast Tanks and anchors to improve the submarines hydrodynamic characteristics. The fairing does not need to withstand the diving depth hydrostatic pressure, so high strength materials are not required. Mild steel and Fibre Reinforced Plastics are commonly used.

Modern submarines have anechoic tiles covering the outer hull to cut down active and passive sonar signature.

10.2.3 Submarine Manufacture

Submarine construction is very expensive. This is because the materials used are expensive and difficult to work with. High strength steels are notoriously difficult to bend, fabricate and weld. Quality control of the manufacturing process is also critical as any out of roundness can severely compromise submarine structural integrity.

Consequently, the number of ship yards with the expertise to manufacture submarines is limited. In the US, Electric Boat a division of General Dynamics and Newport Mews Shipbuilders and Drydocking Company are the only submarine manufacturers.

10.2.4 Submarine General Arrangement

10.2.4.1 Main Ballast Tanks

Figure 10.2 shows the location of the Main Ballast Tanks (MBTs) on a submarine. These are by far the largest tanks on board as they have to able to alter the displacement of the submarine from being positively buoyant (surfaced) when empty to somewhere near neutrally buoyant (submerged) when full. More about this in the next section.

The Main Ballast Tanks are “soft tanks” because they do not need to withstand the hydrostatic pressure when the submarine is submerged. This is because they will be full at the submerged depth with the pressure equalized across them.

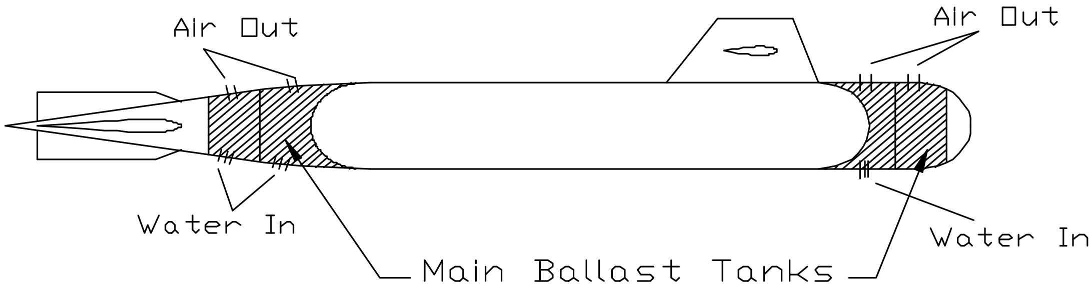

Figure 10.2 - Location of Typical Submarine’s Main Ballast Tanks

10.2.4.2 Variable Ballast Tanks

In addition to the MBTs there are other tanks required to ‘fine tune’ the displacement and trim characteristics of the submarine once it is submerged. These are called variable ballast tanks, Figure 10.3 shows their usual location.

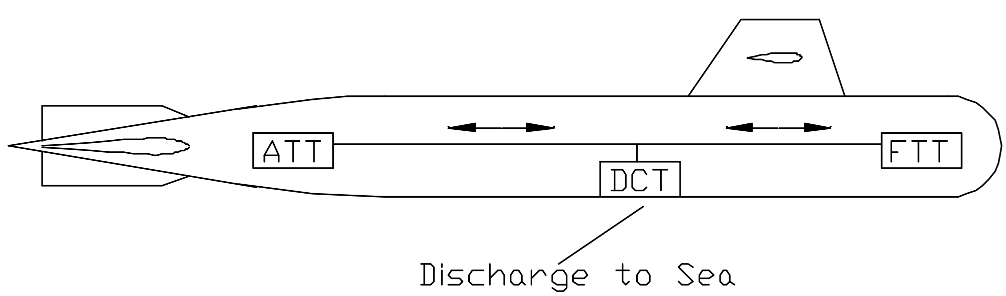

Figure 10.3 - Location of Variable Ballast Tanks

- **Depth Control Tank (DCT).** The DCT is used to alter the buoyancy characteristics of the submarine once it is submerged. For reasons covered in the next section, environmental factors can often cause the submarine to move from a neutrally buoyant condition to being negatively or positively buoyant. Moving water in or out of the DCT can compensate for this. The DCT is termed a ‘hard tank’ because it can be pressurized to submergence pressure allowing its contents to be “blown” overboard..

- **Trim Tanks.** As the name suggests these are used to control the trim of the submarine. Submarines are very sensitive to longitudinal weight shifts, additions and removals. Moving water between the after and forward trim tanks can compensate for these changes. They are ‘soft tanks’ because they are not required to withstand the external hydrostatic pressure.

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10.3 Submarine Types

Since the beginning of this century, the design and hence the effectiveness of submarines has advanced considerably. The modern submarine is a true submersible rather than a boat capable of submerging for brief periods. Modern submarines have various configurations depending upon their role. 3 of the major USN configurations follow.

10.3.1 Ohio Class Submarine

Figure 10.4 shows the configuration of a Ohio Class Submarine. Its Submarine Launched Ballistic Missiles (SLBMs) are carried after the sail. Note its displacement is larger than many of the surface combatants of the USN. Also note the fair-water plane on the sail.

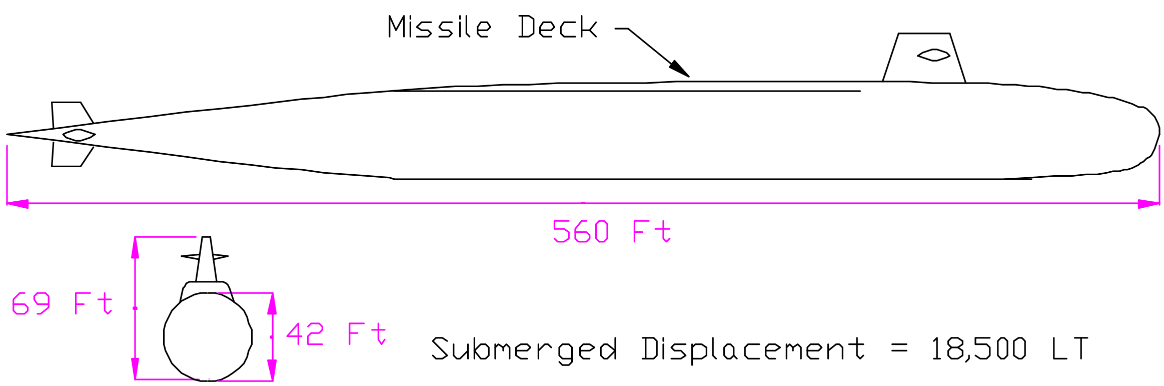

Figure 10.4 - Ohio Class Submarine Characteristics

10.3.2 Los Angeles Class (SSN688)

Figure 10.5 shows the configuration of the SSN688 “Los Angeles Class”.

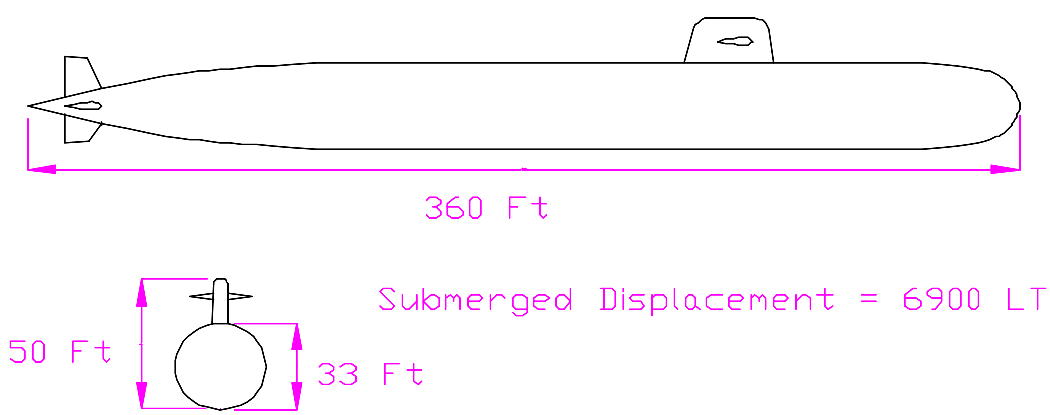

Figure 10.5 - SSN688 Characteristics

10.3.3 Improved SSN688

Improved SSN688 and the Seawolf have replaced the fair-water plane with a bow plane. The purpose of this plane will be covered later. Positioning the plane at the bow allows it to be retracted, a requirement when the submarine is traveling at high speed and when breaking the arctic ice. Figure 10.6 shows the configuration.

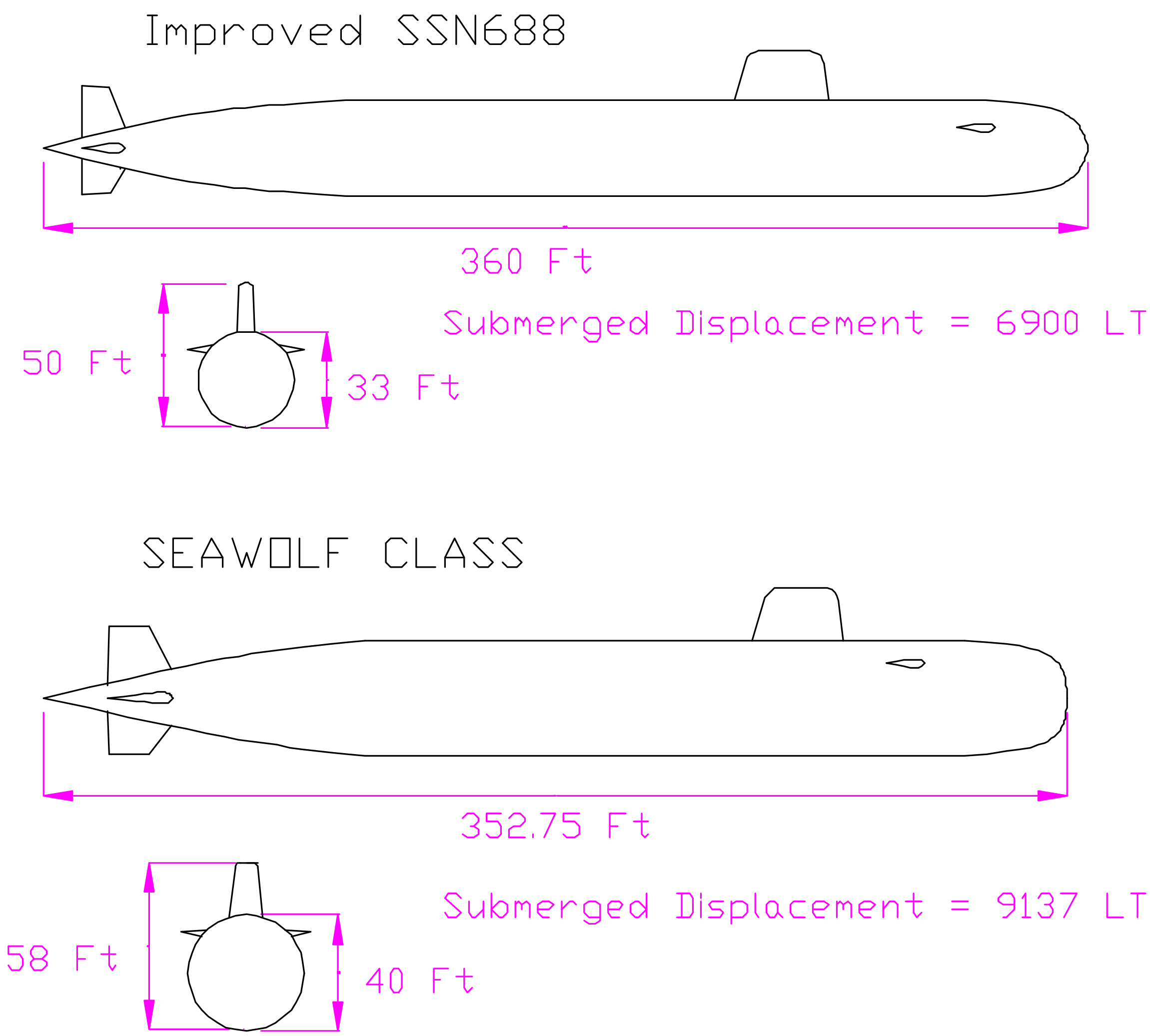

Figure 10.6 - Improved SSN688 and Seawolf Characteristics

10.4 Submarine Hydrostatics

Just like a surface ship, submarines obey the principles of static equilibrium and Archimedes. The submarine experiences a buoyant force equal to the weight of liquid it displaces. When surfaced or neutrally buoyant, this buoyant force is equal to the weight of the submarine (its displacement).

$$\begin{array}{llr} \textit{Archimedes} & & F_B = \rho g \nabla \\ \textit{Static Equilibrium} & & \Delta = F_B \\ & \therefore & \Delta = \rho g \nabla \end{array}$$

10.4.1 Neutral Buoyancy

A surface ship automatically maintains static equilibrium by alterations in its draft. By changing its draft, its submerged volume is altered to reflect any changes to its displacement with weight removals or additions or for any changes in water density.

Unfortunately, a submerged submarine is given no such luxury. The crew must actively maintain a state of static equilibrium by changing the weight of the submarine. This is because the submerged volume of a submarine is constant (at a given depth). Hence the need for a DCT that will compensate for changes in the environment.

10.4.1.1 Salinity

Water density (ρ) will change whenever there is an alteration in its salinity level. This is a fairly frequent occurrence, for example:

- Changes in salinity are common when operating near river estuaries or the polar ice cap.

- Due to constant evaporation, the Mediterranean Sea has a higher salinity level than the oceans.

Example 10.1: The 8000LT USS Hardluck is submerging in Long Island Sound to conduct a "Tiger Cruise". The water temperature is 75^{0}F and Long Island Sound is diluted by 10% fresh water. The Diving Officer calculated the trim for the open ocean. How should the trim be corrected?

@ 75^{0}F ρ_{fresh} = 1.9350 lb-s^2/ft^4

ρ_{salt} = 1.9861 lb-s^2/ft^4

Solution:

In the open ocean the submarine is neutrally buoyant.

$$\therefore \quad \Delta = \rho g \nabla$$

$$\nabla = \frac{\Delta}{\rho g} = \frac{8000\text{ LT } \ 2240\text{ lb/LT}}{1.9861\text{ lb-s}^2/\text{ft}^4 \ \ 32.17\text{ ft/s}^2}$$

$$\nabla = 280{,}470\text{ ft}^3$$

The water in Long Island Sound is 10% fresh, 90% salt

$$\rho_{LIS} = 10\%\,\rho_{fresh} + 90\%\,\rho_{salt}$$

$$\rho_{LIS} = \frac{10}{100}.\frac{1.9350\text{ lb-s}^2}{\text{ft}^4} + \frac{90}{100}.\frac{1.9861\text{ lb-s}^2}{\text{ft}^4}$$

$$\rho_{LIS} = \frac{1.9810\text{ lb-s}^2}{\text{ft}^4}$$

So the buoyant force (F_B) acting on the submarine in Long Island Sound can be found.

$$F_B = \rho g \nabla$$

$$F_B = \frac{1.9810\text{ lb-s}^2}{\text{ft}^4}\ \frac{32.17\text{ ft}}{\text{s}^2}\ 280{,}470\text{ ft}^3$$

$$F_B = 1.787 \text{ x } 10^7\text{ lb} = 7979\text{ LT}$$

Hence submarine displacement (8000LT) is greater than the buoyant force (7979LT). The submarine is acting heavy. To compensate, 21LT of water must be pumped out of the DCT.

10.4.1.2 Water Temperature

Changes in water temperature are common throughout the ocean. Temperature effects water density which in turn effects the magnitude of the buoyant force.

Example 10.2: An 8000LT submarine exits the Gulf Stream where water is 85°F and enters 65°F water. How much water will the Diving Officer need to flood or pump.

$$\rho \text{ @ } 85°F = 1.9827 \text{ lb-s}^2/\text{ft}^4$$
$$\rho \text{ @ } 65°F = 1.9890 \text{ lb-s}^2/\text{ft}^4$$

Solution:

The submarine is neutrally buoyant in the gulf stream.

$$\Rightarrow \quad \Delta = \rho g \nabla$$
$$\nabla = \frac{\Delta}{\rho g} = \frac{8000 \text{ LT} \; 2240 \text{ lb/LT}}{1.9827 \text{ lb}\cdot\text{s}^2/\text{ft}^4 \; 32.17 \text{ ft/s}^2}$$
$$\nabla = 280{,}950 \text{ ft}^3$$

As it leaves the gulf stream the water density changes which alters the size of the buoyant force.

$$F_B = \rho g \nabla$$
$$F_B = \frac{1.9890 \text{ lb}\cdot\text{s}^2}{\text{ft}^4} \; \frac{32.17 \text{ ft}}{\text{s}^2} \; 280{,}950 \text{ ft}^3$$
$$F_B = 1.798 \times 10^7 \text{ lb} = 8025 \text{ LT}$$

So the submarine displacement is 25 LT smaller than its buoyant force. The Diving Officer will have to flood 25 LT of water into the DCT.

10.4.1.3 Depth

As a submarine increases its depth the increasing hydrostatic pressure increases the stress on the hull. This stress then strains the hull. The hull shrinks. So the submerged volume of a submarine decreases with depth which in turn reduces its buoyant force. So to maintain neutral buoyancy, water must be pumped from the DCT reducing the submarine displacement to keep pace with the smaller F_B.

This effect has been accentuated with the introduction of anechoic tiles mentioned in section 10.2. They are compressed when operating at modern maximum diving depths.

10.4.2 Neutral Trim

The second goal the submarine crew is actively seeking is neutral trim. Trim is particularly sensitive on a submarine once submerged due to the lack of a waterline.

You may recall from Chapter 3 that the distance of the metacenter above the keel can be found by adding BM (the metacentric radius) to KB. This can be used in either the transverse or longitudinal directions to find KM_T or KM_L respectively. Figure 10.7 graphically illustrates the relationships for a surface ship.

BM_L is very much larger than BM_T because ships tend to be longer than they are wider and so their second moment of area is much greater longitudinally than transversely.

$$\overline{BM}_L = \frac{I_L}{\nabla_S} \qquad \overline{BM}_T = \frac{I_T}{\nabla_S}$$

ships are bigger longitudinally than they are wider transversely

$$\therefore \quad I_L \gg I_T$$

$$\therefore \quad \overline{BM}_L \gg \overline{BM}_T$$

The situation for the surfaced submarine is quite similar to the surface ship. Figure 10.8 illustrates the geometric relationships for a surfaced submarine. You will notice that G is situated below B; the importance of this will become evident in the next section.

In fact the location of M_T is much higher than it would be normally. For clarity, M_T has been shown significantly above the location of B, in practice the distance between the 2 locations is very small while the submarine is surfaced.

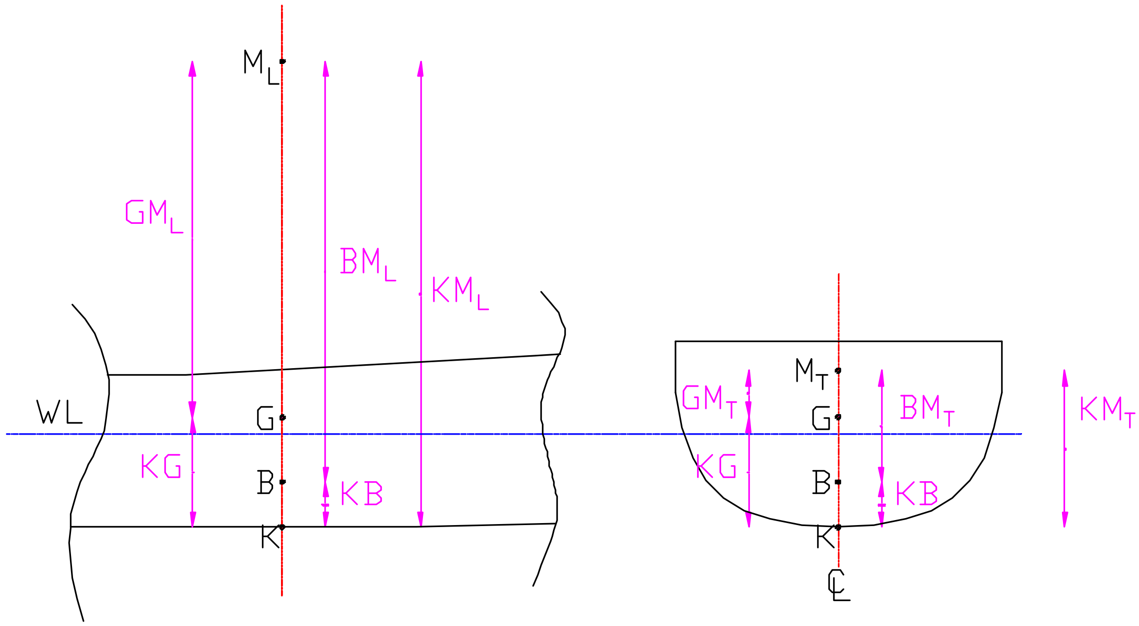

Figure 10.7 - K,B,G & M Geometry for Surface Ship

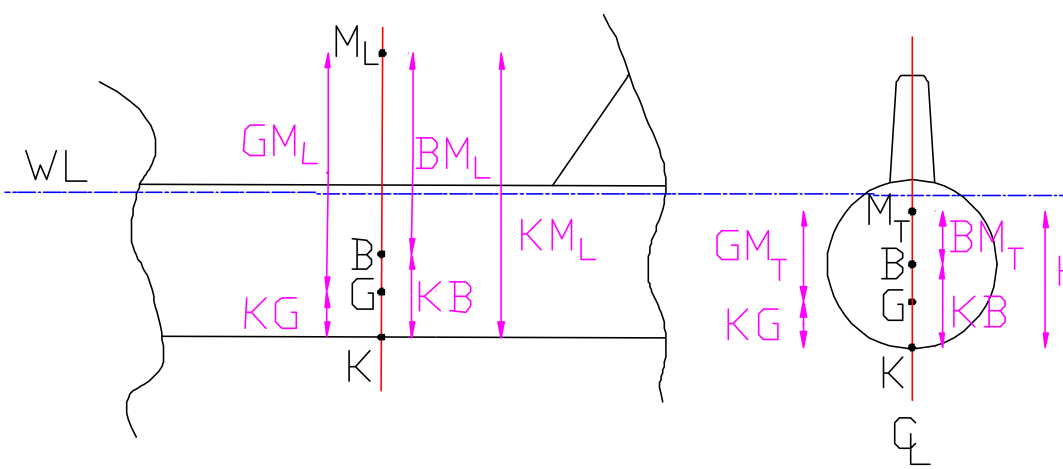

Figure 10.8 - K,B,G & M Geometry for Surfaced Submarine

As the submarine submerges, its waterplane disappears. With no waterplane there is no second moment of area of the waterplane and so no metacentric radius. Hence the center of buoyancy and the metacenter are both located at the centroid of the underwater volume - the half diameter point.

$$\overline{GM_L} = \overline{KB} + \overline{BM_L} - \overline{KG} \qquad \overline{GM_T} = \overline{KB} + \overline{BM_T} - \overline{KG}$$

but as the waterline disappears

$$I_L = I_T = 0$$

$$\overline{BM_L} = \overline{BM_T} = 0$$

So

$$\overline{GM_L} = \overline{KB} - \overline{KG} \qquad \overline{GM_T} = \overline{KB} - \overline{KG}$$

So

$$\overline{GM_L} = \overline{GM_T} = \overline{BG}$$

What actually happen is that as the submarine submerges, B moves vertically up very slightly because of the additional hull volume and sail being submerged and M moves vertically down as the water-plane disappears. When finally submerged, the positions of B, M_T and M_L are coincident. Figure 10.9 shows the geometric relationships for a submerged submarine.

A consequence of this is the submerged submarine has the same initial stability characteristics longitudinally as it does transversely.

Because submarines are much longer than they are wide, the submerged submarine is very sensitive to trim. This accounts for the need for trim tanks.

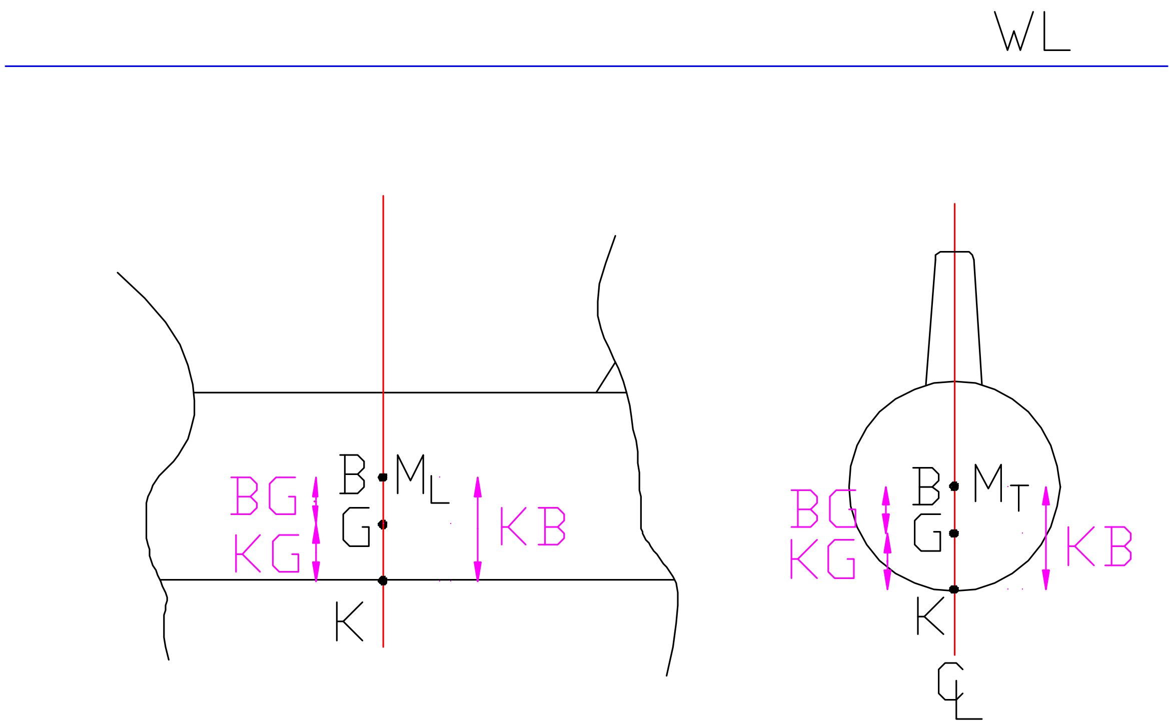

Figure 10.9 - K,B,G & M Geometry for Submerged Submarine

10.4.2.1 Transverse Weight Shifts

You may recall from Chapter 3 that the analysis of a transverse weight shift in a surface ship involved the situation shown in Figure 10.10.

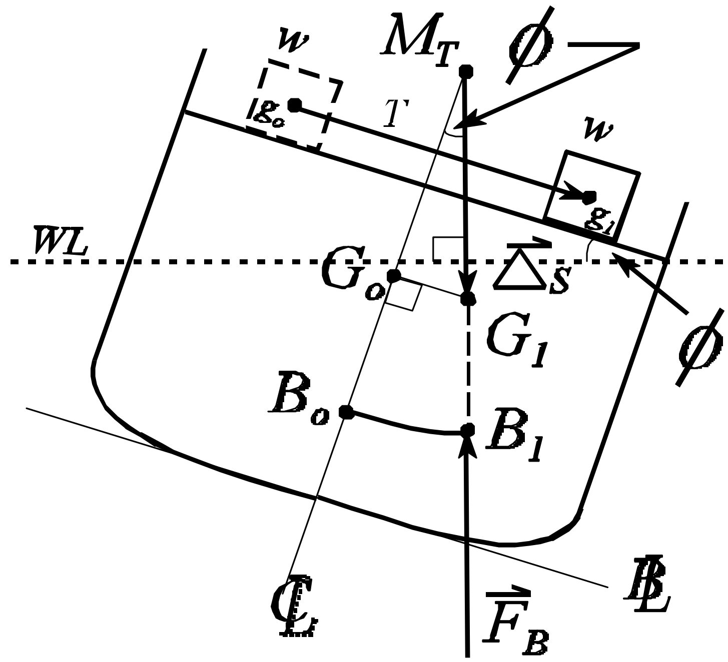

Figure 10.10 - The Inclining Surface Ship

From the geometry of the triangle $G_0G_TM_T$ and from a knowledge of the size and distance the weight was being shifted an equation could be formulated as follows.

$$\tan\phi = \frac{\overline{G_0G_t}}{\overline{G_0M_T}} \qquad \overline{G_0G_t} = \frac{wt}{\Delta_S}$$

$$\Rightarrow \quad \Delta_S\,\overline{G_0M_T}\,\tan\phi = wt$$

This equation was then used to estimate the value of GM_T of a ship in the Inclining Experiment. With GM_T known it is then possible to calculate the vertical center of gravity, KG.

Unfortunately, this equation relies upon the existence of the triangle $G_0G_TM_T$ which is only true at small angles. At larger angles the metacenter is not stationary and moves about causing any calculation using this system to be inaccurate. Angles of list at large angle are only available from an analysis of the curve of statical intact stability, the list angle corresponding to the intercept of the Righting Arm Curve with the x axis.

For a submerged submarine, with both the Center of Buoyancy (B) and the Metacenter (M) being in the same location, calculation of the heeling angle is greatly simplified. Figure 10.11 shows a submarine listing due to a TCG.

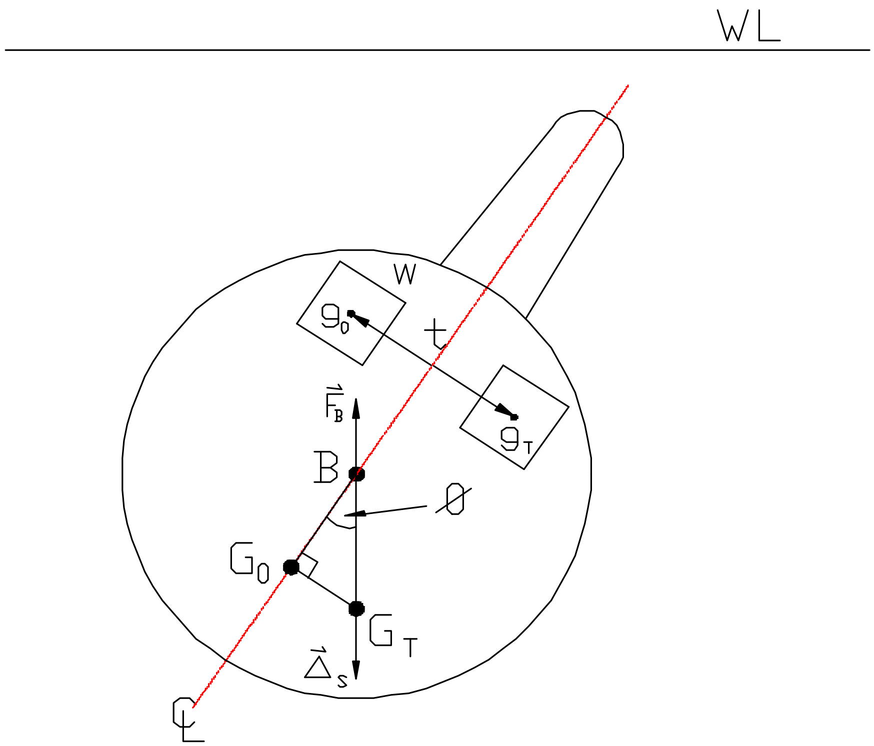

Figure 10.11 - The Inclining Submerged Submarine

The analysis of this situation involves the triangle G_0G_TB and a knowledge of the weight shift.

$$Tan\,\phi = \frac{\overline{G_0G_t}}{\overline{BG_0}} \qquad \overline{G_0G_t} = \frac{wt}{\Delta_S}$$

$$\Rightarrow \quad \Delta_S\,\overline{BG_0}\,Tan\,\phi = wt$$

This equation is good for all angles as the position of B will be constant for any list. With a knowledge of the distance BG_0, the submarine displacement Δ, and the weight shift, the angle of list can always be determined.

Example 10.3: A submerged submarine weighs 7200 LT with KB = 15 ft, KG = 13.5 ft. A piece of machinery weighing 6 LT is moved from 10 ft stbd of the centerline to a position 13 ft port of the centerline. Its distance above the keel does not change. What is the angle of list created by this movement?

Solution:

Using the equation we have just proved.

$$wt = \Delta_S \overline{BG_0} \, Tan\phi$$

$$Tan\phi = \frac{wt}{\Delta_S \overline{BG_0}}$$

$$Tan\phi = \frac{6 \text{ LT } \; 23 \text{ ft}}{7200 \text{ LT } \; 1.5 \text{ ft}} = 0.0128$$

$$\phi = 0.73 \text{ degrees}$$

10.4.2.2 Longitudinal Weight Shifts

For a surface ship, the analysis of a longitudinal weight shift is involved. The process is complicated by the ship trimming about the center of floatation (F) which is seldom at midships.

For a submerged submarine, the analysis of longitudinal weight shifts is exactly the same as in the transverse case. This is because the characteristics of a submerged submarine are exactly the same longitudinally as they are transversely, both being controlled by the distance BG_0. Hence the following equation holds for all angles of trim.

$$wl = \Delta_S \overline{BG_0} \, Tan\theta$$

Because submarines are much longer than they are wide, the value of the longitudinal moment arm (l) can be much larger than the transverse moment arm (t). Hence the need for trim tanks that can compensate for longitudinal weight shifts.

Example 10.4: A submarine weighs 7200 LT and has zero trim. KB = 15 ft, KG = 13.5 ft. 40 submariners weighing 200 lb each move aft a distance of 300 ft.

a. What will be the new trim angle.

b. How much water must be transferred between the 2 trim tanks to return the trim to zero. The distance between trim tanks is 200ft.

Solution:

a. Using the equation above.

$$wl = \Delta_S \overline{BG_0}\, Tan\theta$$

$$Tan\theta = \frac{wl}{\Delta_S \overline{BG_0}}$$

$$Tan\theta = \frac{40\ (200\ \text{lb})\ (300\ \text{ft})}{(7200\ \text{LT})\ (2240\ \text{lb/LT})\ (1.5\ \text{ft})} = 0.0992$$

$$\theta = 5.67\ \text{degrees}$$

b. To return the trim to zero, the moment created by shifting the water must be equal and opposite to the moment created by the moving people.

$$40\ (200\ \text{lb})\ (300\ \text{ft}) = w\ (200\ \text{ft})$$

$$w = 12{,}000\ \text{lb} \quad \textit{pumped from aft to fwd}$$

NB: Many early submarines would come to the surface after firing a torpedo. This was due to the combination of loss in displacement and the loss of a significant moment helping to trim the sub. This surfacing phenomena was very unpopular with submarine crews, especially when they missed!

10.5 Submarine Intact Stability

As with the case of weight shifts, the absence of a waterplane and the stationary nature of B greatly simplifies the analysis of submerged submarine hydrodynamics.

Earlier Figures indicated that the Center of Gravity (G) has to be below the Center of Buoyancy (B) for the submarine to be stable. Figure 10.12 illustrates this point.

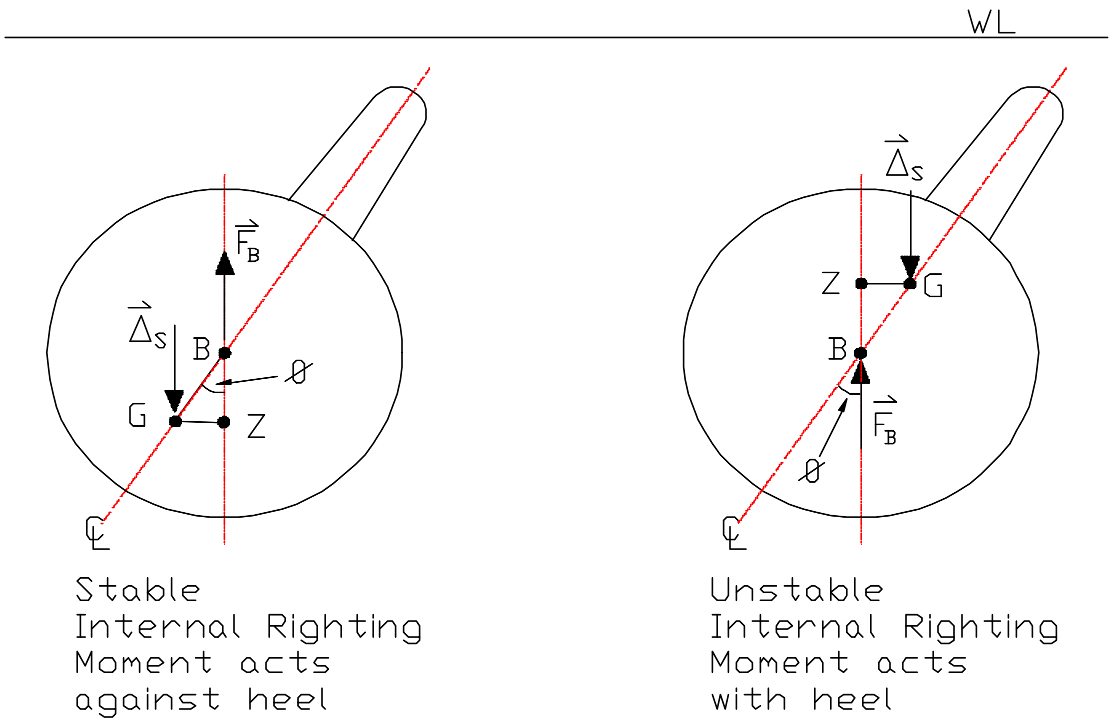

Figure 10.12 - Submarine Initial Stability

The level of stability is wholly dependant upon the distance between B and G (BG). Because this distance is constant, an analysis of the triangle BGZ reveals that the Righting Arm (GZ) is purely a function of the angle of heel.

$$Righting\ Arm = \overline{GZ} = \overline{BG}\,Sin\,\theta$$

This equation holds for all submerged submarines, in all conditions. Hence the curve of statical intact stability will always be a sine curve with a peak value equal to BG. Figure 10.13 shows the curve for all submarines.

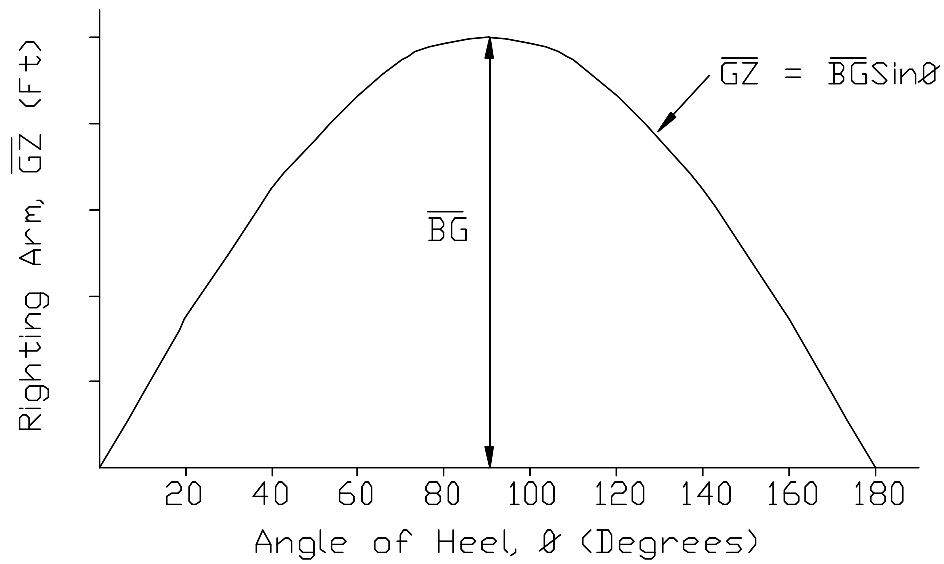

Figure 10.14 - Curve of Intact Statical Stability for Submerged Submarine

Stability characteristics will always be as follows.

- **Range of Stability** - The range of heeling angles through which a Righting Arm is maintained against the heeling motion.

  Range of stability = $0 - 180°$

- **Angle of Maximum Righting Arm** - The angle of heel creating the maximum righting moment.

  Angle of RA_{max} = $90°$

- **Maximum Righting Arm** - The size of the maximum righting arm.

  RA_{max} = BG

- **Dynamic Stability** - The energy required to move the submarine slowly through all angles of heel until capsize

  Dynamic Stability = $\Delta_S BG \int_0^{180} \sin\phi \, d\phi$

  = $2 \Delta_S BG$

10.6 Submarine Powering

Submarine powering suffers the same constraints inflicted on surface ships. However, submarines suffer an additional handicap in that they have a requirement to be quiet.

10.6.1 Submarine Resistance

You will recall from Chapter 7 that the resistance of a surface ship is made up from a combination of 3 resistance forms, and is written again below in both dimensional and dimension less terms:

$$R_T = R_V + R_W + R_{AA} \qquad C_T = C_V + C_W$$

where C_V = the viscous resistance of the hull, itself made up from factors associated with its skin resistance and its form.

$$C_V = (1 + K)C_F$$

C_W = the wave making resistance of the hull. This element is caused from the energy the ship loses in making waves.

R_{AA} = the ship's resistance in air (not applicable to a submerged submarine!)

As the surface ship speed changes, the resistance component that contributes the most to the total resistance changes. At low speed, viscous resistance is the main factor. However, as speed increases, wave making becomes the dominant resistance component due to the bigger bow wave and wake being created.

In the case of a surfaced submarine, this is no different. In fact the effect is more pronounced. The surfaced submarine generates a very large bow wave, so wave making resistance is always significant.

When the submarine submerges, the skin friction resistance will increase due to the greater surface area making C_V greater. However, the wave making element disappears provided the submarine is deep enough. Consequently, the modern submarine experiences less resistance when submerged than on the surface, so it has a greater top speed when submerged. A recent article in the Journal Marine Technology claim a Russian Nuclear Attack Submarine of the Northern Banner Fleet achieved a submerged speed of 44.7 knots. This was in 1969!

10.6.2 Submarine Propellers

Modern submarines use highly skewed propellers with an odd number of blades. The governing factors are cavitation and vibration, even at the expense of propeller efficiency.

10.6.2.1 Odd Blade Number

The number of blades is chosen to minimize vibration. An odd number of blades is used because there are an even number of appendages at the stern; a rudder top and bottom, and stern planes port and starboard. An odd number of blades means that no two blades will be entering the disturbed flow behind the appendages at the same time. Therefore, the forces causing vibration will not reinforce each other. Figure 10.14 demonstrates this principle.

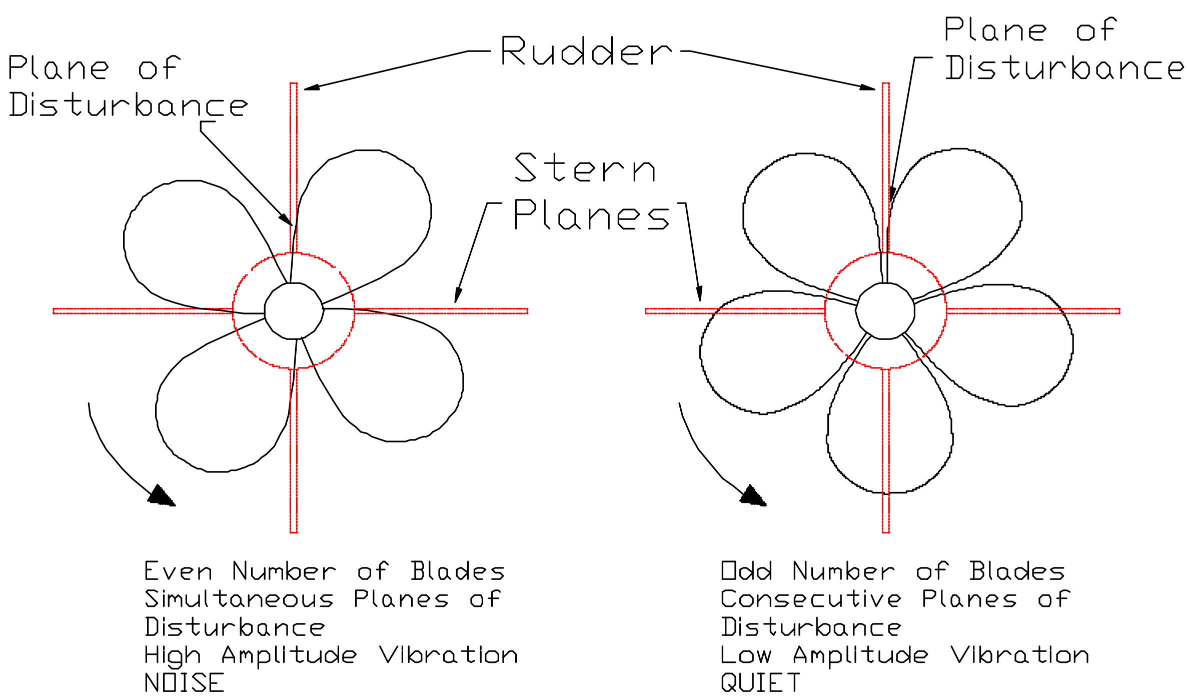

Figure 10.14 - Advantage of an Odd Number of Propeller Blades

10.6.2.2 Skewed Propeller

Skewing the propeller has several advantages.

- **Reduced Vibration.** The entire blade does not enter disturbed flow at the same time. In fact, the blade tip may be leaving as another part of the same blade is entering. The amount of the propeller subjected to a disturbance at any one time is reduced, and therefore vibration is reduced.

- **Reduced Cavitation.** The shape is thought to produce a radial flow near the blade tips which sweeps cavitation sheets into the tip flow (vortices - or rotating flow). Here the cavitation bubbles collapse gradually reducing the noise level.

Unfortunately, highly skewed propellers have some disadvantages.

- Very inefficient for backing.

- Very difficult and expensive to manufacture.

- The unusual shape reduces the strength of the blades.

For the special considerations of submarine operation and the absolute need for stealth, the advantages of the highly skewed propeller outweigh the disadvantages.

10.7 Submarine Seakeeping

You will recall from Chapter 8 that a surface ship will respond to any external forcing function. For ship motions, these will be the 3 translatory motions of surge, sway and heave and the 3 rotational motions of roll, pitch and yaw. Of these 6, heave, pitch and roll are simple harmonic motions because they experience a linear restoring force. If the encounter frequency matches the resonant frequency of either of these, motions will be maximized, particularly for roll which has a sharply tuned response characteristic.

Because surface waves affect water velocities beneath the surface, a submerged submarine can experience the same motions that a surface ship does. In fact, the motion of roll is often very pronounced due to the submarine's cylindrical shape.

10.7.1 Suction Force

In addition to the usual surface ship motions, a submerged submarine running close to the surface is affected by suction forces caused by the water surface, waves and the shape of the hull.

10.7.1.1 Water Surface Effect

When a submarine is traveling near the surface, at periscope depth for instance, a low pressure is created on the top surface of the hull causing a net upward force, or suction force. The magnitude of the suction force depends on speed, depth, and hull shape. A higher speed creates a bigger force. The closer the hull is to the surface, the greater the suction force. Large flat surfaces, like missile decks on SSBN's, create greater suction forces than round SSN hulls.

The effect can be minimized by traveling at very slow speeds while at periscope depth and giving the submarine trim. This latter action places much of the hull farther away from the surface and changes the flow around the hull shape, decreasing the magnitude of the suction force.

10.7.1.2 Wave Action

Wave action on the surface is also responsible for surface suction forces. Water particle velocity decreases with depth. Consequently, the top surface of the submarine experiences faster water velocity and hence lower pressure than the bottom surface.

The suction effect of surface waves may be minimized in two ways. The effect decreases rapidly with increasing depth. Also, the heading angle of the ship relative to the direction of wave motion is important. A submarine traveling beam to the sea experiences greater rolling motions but minimizes the suction force. Unfortunately, it presents a less comfortable ride for the crew.

10.8 Submarine Maneuvering and Control

Just like a surface ship, a submarine controls its course with a rudder and its speed with the engines and screw propeller. However, the submarine has the added complication of controlling its depth.

Submarine depth control can be accomplished in many ways. Making the buoyant force equal the submarine displacement is the obvious technique and was discussed earlier in the chapter. However, a finer and more positive degree of control is often required. This is achieved by equipping the submarine with planes. One set, the stern planes, are located at the aft end of the ship. Fair-water planes are located on the sail. As seen earlier, some modern submarines have bow planes instead of fair-water planes.

The planes are equipped so that their angle of attack may be changed by the operator. Changing the angle of attack will cause the planes to produce lift up or down.

10.8.1 Fair-water Planes

The fair-water planes are used primarily to maintain an ordered depth. Positioning the planes to the "up" position causes an upward lift force to be generated. Since the planes are located forward of the center of gravity, a moment (M) is also produced which causes the submarine to pitch up slightly. However, the dominant effect is the lift generated by the control surface. Figure 10.15 illustrates the effect.

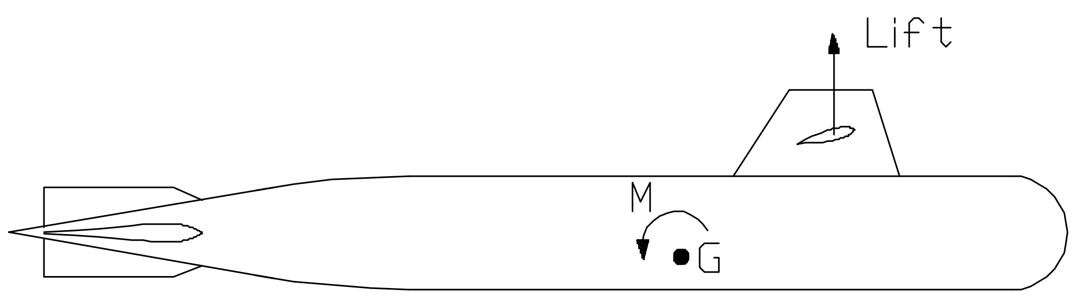

Figure 10.15 - The Effect of the Fair-water Plane

10.8.2 Stern Planes

The stern planes have a much bigger effect on the pitch of the submarine because of their distance from the center of gravity. Positioning the planes as shown in Figure 10.16 creates a lift force in the downward direction. This creates a moment (M) which causes the submarine to pitch up, much like the action of the surface ship's rudder discussed in chapter 9. Once the submarine has an up angle, the hull produces an upward lift force. The net effect is that the submarine rises at an upward angle.

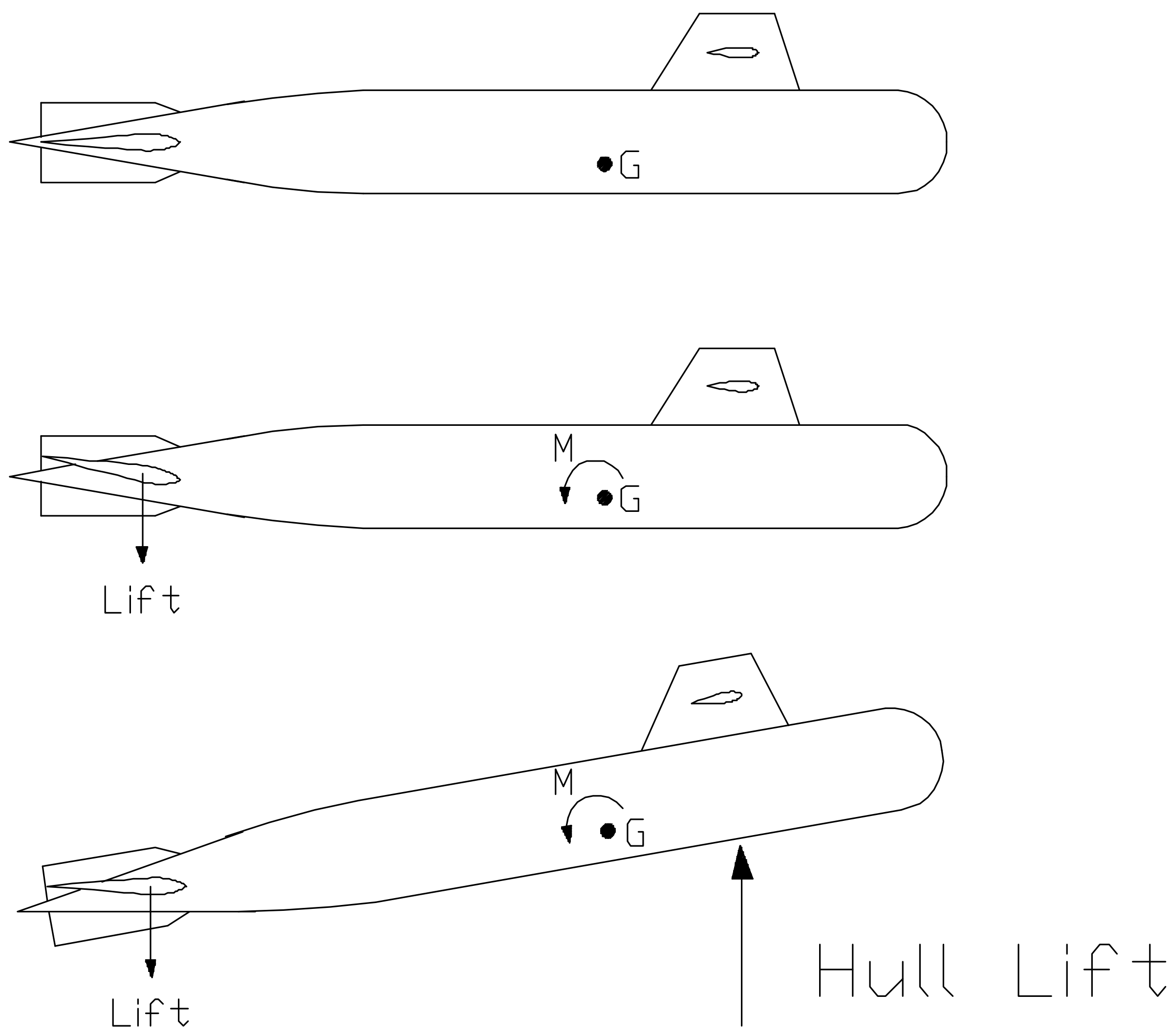

Figure 10.16 - The Effect of the Stern Planes

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HOMEWORK CHAPTER 10

Section 10.2

Construction & Layout

1. Why are submarines constructed with a transverse framing system in preference to a longitudinal framing system?

2. What is "out of roundness?" What is the significance of this term in relation to submarine structures?

General Arrangement

3. What is the difference between hard tanks and soft tanks?

4. Draw a diagram showing the inner hull, outer hull, and main ballast tanks. Which of these must be able to withstand submergence pressure?

Section 10.4

Hydrostatics

5. Qualitatively describe the changes (if any) that occur to a surfaced submarine's weight (displacement) and buoyant force as it moves from fresh water to salt water.

6. Qualitatively describe the changes (if any) that occur to a submerged submarine's weight (displacement) and buoyant force as it moves from fresh water to salt water.

7. How does increasing depth affect submarine buoyancy?

8. A submerged SSN688 weighing 6900 LT has been patrolling the arctic pack ice. It is now moving south into the North Atlantic. While under the pack ice, the boat trim was set assuming a 70% salt, 30% fresh water content at 30 degrees F. What action must the Diving Officer take to maintain neutral stability if the water in the North Atlantic is 100% salt at 35 degrees F?

    @ 30 degrees F - $\tilde{n}_{fresh} = 1.9399$ lb-s^2/ft^4
    @ 35 degrees F - $\tilde{n}_{fresh} = 1.9400$ lb-s^2/ft^4
    @ 30 degrees F - $\tilde{n}_{salt} = 1.9947$ lb-s^2/ft^4
    @ 35 degrees F - $\tilde{n}_{salt} = 1.9945$ lb-s^2/ft^4

9. A submerged submarine has a trim angle of 2 degrees up. It is desired to pump water between the forward and after trim tanks to correct the trim to zero degrees. The tanks are 300 ft apart. Its weight is 7500 tons, KG = 13.5 ft and KB = 15.7 ft.

   a. Should water be pumped from after trim to forward trim or from forward trim to after trim?

   b. What is the effect of pumping water in the direction you chose in a. on the submarine's LCG?

   c. What is the relationship between LCB and LCG in the initial condition? Final condition? Use a diagram.

   d. How much water must be pumped? Use pounds.

Section 10.5

Stability

10. For a submarine, KB = 14.5 ft and KG = 13 ft. Displacement is 6500 LT.

   a. Write the equation for the Curve of Intact Statical Stability

   b. Compute the Maximum Righting Moment

   c. At what angle does the Maximum Righting Moment occur?

   d. What is the Range of Stability?

   e. Using integral calculus, compute dynamical stability.

   f. Repeat all of the above for KG = 14 ft. Compare the results.

Sections 10.6, 10.7 & 10.8

Powering, Seakeeping & Control

11. Why does it make sense to use an odd number of blades on a submarine propeller?

12. Name two advantages and two disadvantages of skewed propellers for submarines.

13. Describe two sources of surface suction.

14. Draw a profile of a submarine showing the rudder, fairwater planes and stern planes. What are each of these control surfaces used for?